Development of a Polarized Helium-3 Source for RHIC and eRHIC

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The addition of a polarized ^3He ion source for use at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory would enable a host of new measurements, particularly in the context of a planned eRHIC. We are developing such a source using metastability exchange optical pumping to polarize helium-3, which will be then transferred into RHIC's Electron Beam Ion Source for ionization. We aim to deliver nuclear polarization of near 70%, and roughly 10^{11} doubly-ionized $^3\text{He}^{++}$ ions will be created in each 20 μsec pulse. We discuss the design of the source, and the status of its development.

Keywords: ^3He polarization; ion beam source.

1. Introduction

A polarized neutron beam would provide a crucial tool in the exploration of nucleon structure, especially with the advent of an electron-ion collider. The small magnetic moment of deuterium precludes its direct use in RHIC, but polarized ^3He offers an attractive alternative. Nearly 90% of the time, ^3He is found in its spatially symmetric S-state, in which its protons are in a singlet and the nuclear spin is carried by the neutron. In the context of spin asymmetries then, a polarized ^3He beam can act as a surrogate for a polarized neutron beam, whose magnetic moment allows manipulation in the RHIC rings.¹

1.1. Source Design

Our design² leverages the existing Electron Beam Ion Source (EBIS),³ which allows the ionization and extraction of nearly any atomic species. Gas introduced into EBIS

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is ionized by a 10 A electron beam and trapped in a 5 T solenoid field. Drift tubes in the solenoid apply trapping and extraction electric potentials, allowing EBIS to deliver nearly 10^{12} charges per pulse. EBIS has provided He^{2+} , Ne^{5+} , Ar^{10+} , Fe^{20+} , and Ti^{18+} for NASA's space radiation laboratory and Cu^{11+} , Au^{32+} and U^{39+} for recent RHIC runs.

Metastability exchange optical pumping⁴ offers a convenient method to provide EBIS with pure samples of polarized ^3He gas at the required rates. In MEOP, an RF discharge excites a small portion of the ^3He atoms from ground into the 2S metastable state. A circularly polarized laser then pumps 2S to 2P transitions in the metastable population, at the same time either increasing or decreasing the magnetic quantum number by 1 in the aligning magnetic field. The resulting polarization of the metastable state atoms is then transferred back to the ground state atoms by metastability exchange collisions, allowing the polarization of the entire sample to be enhanced. MEOP has traditionally been performed at low field (30 G) and pressure (1 torr), although recent development has shown this technique can be performed at much higher magnetic fields and pressures.⁵

The most significant depolarizing effect we will encounter during the introduction of polarized gas into EBIS will come from depolarizing magnetic field gradients. The short time scale before extraction and very high field inside EBIS result in very small expected depolarization from charge exchange with any remaining singly ionized helium or from recombination with free electrons. However, performing MEOP in the space near the 5 T magnet, as well as transferring the polarized gas into EBIS, may be subject to significant depolarization from magnetic field gradients. Figure 1 shows the expected relaxation time in and around the EBIS solenoid, as calculated from an EBIS field map and formula from Scheerer and Walters.⁶ Dark spots in the plot show areas where polarizing or transferring the gas would incur significant losses in final polarization.

Fig. 1. A map in mm of the expected polarization relaxation time of 1 torr helium 3 due to magnetic field gradients in the space in and around the EBIS 5 T solenoid magnet.

2. Development Status

Our efforts have been concentrated on the polarization and transfer of polarized gas in regions of field gradients. A MEOP polarizer has been built at MIT to undertake initial investigations, including the measurement of polarized ^3He via RF discharge light⁷ and the observation of diffusion of polarized gas through depolarizing gradients.⁸ A probe laser polarimeter has also been developed to allow polarization measures at low or high magnetic fields, a technique pioneered at the Kastler-Brossel Laboratory in Paris.⁹ In the summer of 2014, a second polarizing apparatus was assembled at BNL to perform tests to assess the viability of two options for the final source design: low field or high field MEOP.

2.1. Low Field Polarization

In the low field MEOP option, polarization would be performed in the stray field of the 5 T magnet, below 100 G, and the gas would be transferred through the stray field into the EBIS solenoid. Candidate locations for the polarizer are expected to have less than 10 second relaxation times, as seen in Fig. 1, so correction of the field would be necessary to reach the goal polarization of 70%. We expect an anti-Helmholtz coil magnet to provide adequate correction for field gradients in the region in and around the polarizer.

Initial polarization tests at BNL in the stray field of the spare EBIS 5 T solenoid have proved promising. With the polarizer at a candidate location outside the 5 T spare solenoid, polarization was attempted using the stray field itself as the only aligning magnetic field. While a short relaxation time of 6 seconds was measured, closely matching the expected value from Fig. 1, the steady-state polarization reached 28% as the optical pumping laser was increased in power to near 10 W. Adding a 30 G field along the axis of the polarizer using a small solenoid increased both the polarization to 38% and the relaxation time to about 20 seconds.

2.2. High Field Polarization

In a high field MEOP case, the polarizer would be located close to or within the 5 T EBIS field, removing the need to transfer through the stray field. Polarizations exceeding 80% have been reported using fields of 1.5 T and higher,¹⁰ a further bonus of this alternative. A sealed cell with 1 torr of ^3He was placed in the uniform field region of the EBIS spare solenoid, and polarization was attempted at 1 to 4 T with 3 W of optical pumping power. Polarization was measured with the probe laser tuned to probe specific 2S to 2P transitions, monitoring aligned and anti-aligned states.

Preliminary results of steady-state polarization above 1 T have been surprisingly strong. Although the sealed cell never reached higher than 60% during polarization at 30 G, at 2, 3 and 4 T, 80% nuclear polarization was observed with relative ease by ensuring very low RF discharge levels. The high field polarization apparatus is shown in Fig. 2.

Fig. 2. Sealed ^3He cell inside the 5 T spare EBIS solenoid with very bright RF discharge. In the foreground are the pumping laser guide and optics, with the probe laser guide and optics, and photodiode package to their right and left, respectively.

3. Next Steps

The promising results from our tests at Brookhaven pave the way for further development. We plan to correct the stray field of the solenoid using correction coils, and begin tests of gas transfer into the spare solenoid uniform field region. Although our high field polarization results were exciting, we are building an NMR system to ensure the accuracy of these results. Should high field polarization prove the best option, significant design work is needed to allow polarization without disruption of EBIS's successful operation. We hope to perform tests of ionization and extraction of polarized gas this year.

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